DTU Library

An Integrated Framework for Life Cycle Engineering

Hauschild, Michael Zwicky; Herrmann, Christoph; Kara, Sami

Published in:
Procedia CIRP

Link to article, DOI:
10.1016/j.procir.2016.11.257

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 61 (2017) 2 – 9

www.elsevier.com/locate/procedia

The 24th CIRP Conference on Life Cycle Engineering

An Integrated Framework for Life Cycle Engineering

Michael Z. Hauschild[1,*], Christoph Herrmann[2], Sami Kara[3]

[1]Department of Manufacturing Engineering and Management,Technical University of Denmark, Produktionstorvet Building 424, Kongens Lyngby, DK-2800, Denmark

[2]Chair of Sustainable Manufacturing and Life Cycle Engineering, Insitute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Germany

[3]Sustainable Manufacturing & Life Cycle Engineering Research Group, School of Mechanical & Manufacturing Engineering, The University of New South Wales, Sydney, NSW 2052 Australia

* Corresponding author. Tel.: +45-4525-4664. *E-mail address:* mzha@dtu.dk

Abstract

Life Cycle Engineering (LCE) was introduced as a concept more than 24 years ago in order to address emerging concerns about environmental sustainability in engineering. A number of methods and tools have been introduced to operationalise the LCE concept, but since then, the scope of sustainability has broadened, and as a result, LCE has evolved in parallel with other disciplines with similar aims. Currently, in addition to LCE, there exist a number of concepts such as Industrial Ecology, Cleaner Production, Life Cycle Management (LCM), Industrial Symbiosis, and Circular Economy. As a result, orientation becomes challenging and a framework to integrate them is required. The paper aims to introduce an integrated framework for LCE defining the concept and its boundaries, and it argues for the need to reorientate LCE towards the environmental dimension of sustainability. Through an integrated top-down and bottom-up approach, the framework establishes a relationship between LCE and the other concepts and positions them relative to the planetary boundaries and the concept of absolute environmental sustainability.

Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering

Keywords: Life Cycle Engineering; Absolute sustainability, Planetary boundaries, Integrated framework

1. Introduction

With the 1987 report 'Our common future' from the UN Commission for Environment and Development (the 'Brundtland Commission'), sustainability was positioned centrally in the discussion of our development of the world [1]. A sustainable development was identified as meeting the needs of the present without compromising the ability of future generations to meet their own needs [2]. The report introduced the point that a sustainable development at the same time must consider both the environmental dimension and the social and economic dimensions. This inspired the concept of the triple bottom line to the corporate world, challenging companies to consider all three dimensions of sustainability and at the same time optimise the use of the economic capital, the human capital and the environmental capital [3]. Driven by the expectations of financial markets, most companies still consider the economic bottom line as more important than the other two. At a societal level, weak sustainability allows full trade-offs between the three dimensions, meaning that erosion of the natural capital can be compensated by increases in human and economic capital [4]. Realising the fundamental role that the environmental dimension plays for the other two sustainability dimensions, Goodland [5] defined environmental sustainability as seeking to"… improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans". Recent developments in the understanding of the strain that our societies put on the natural environment and the consequences that the resulting changes may have on its life support functions now and in the future have reinforced

Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.11.257

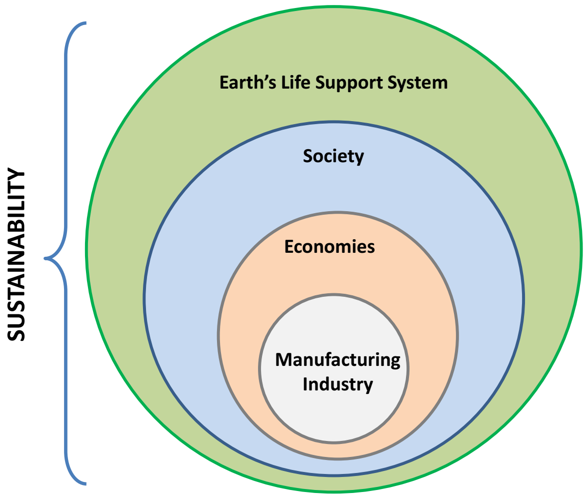

Fig. 1. The three dimensions of sustainability according to [6]

stronger sustainability definitions where the social and economic dimensions are nested inside the environmental dimension as illustrated in Figure 1.

The IPAT equation, based on work by Erlich and Holdren [7] and Commoner [8] supports an analysis of the challenge that central driving forces pose to the development of the production and consumption patterns in a future sustainable society. As seen in Eq. 1, it presents the total environmental impact (I) as a function of the central drivers represented by the human population (P), the human affluence (A, representing the material standard of living per capita) and the technology factor (T, representing the environmental impact caused by our technology per created value).

$$I = P \cdot A \cdot T \quad (1)$$

To get an idea of the challenge to ensure environmental sustainability, consider the following conditions for a sustainable climate change impact (I) in 2050: According IPCC [9], we need to reduce man-made emissions of greenhouse gases in 2050 by between 30 and 70% of the current level (and by close to 100% in 2100) in order to have a reasonable probability to stay below the 2 degree target that was agreed for the global temperature increase at the COP21 meeting in Paris 2015. Meanwhile, the global population (P) is predicted to increase by a factor 1.4 compared to today to reach 9.75 billion in 2050 [1]. Thanks to the strong economic development in many developing regions, the global average affluence (A) is expected to increase, and here, a factor 2 seems to be a conservative estimate. To achieve a 70% reduction in I, the technology factor T has to compensate the increases in P and A, and decrease by close to a factor 10 ($1.4 \times 2/0.3$).

2. LCE Framework

The technology factor T is the reciprocal of the eco-efficiency of the technology – high eco-efficiency entails high value creation with small environmental impact [10]. The environmental impact can be measured using life cycle assessment, LCA, and it is typically used as a relative measure in comparisons of products or technologies. Historical development has demonstrated that exclusively focusing on eco-efficiency is insufficient to ensure sustainability. In the IPAT equation, there are interdependencies between the factors, and a coupling between A and T has been observed e.g. for lighting technologies [11] meaning that improvements of several orders of magnitude in efficiency (1/T) over the last centuries have been more than neutralised by accompanying increases in consumption (A). Indeed, an increase in technology efficiency may drive increases in consumption through what is characterised as an economic rebound effect [12]. Development of sustainable production and consumption requires that the focus on eco-efficiency be accompanied by a focus on eco-effectiveness, ensuring that needs fulfilment is achieved in a manner that 'is in accordance with the overall conditions that must be met by a sustainable society' [11]. Absolute boundaries for the environmental impact have been proposed as a guidance to assess eco-effectiveness at the level of countries and even individual companies [13-14]. The planetary boundary concept proposed by Steffen et al. [15] addresses environmental processes affecting the stability of planetary self-regulating systems, and the proposed boundaries are at the global level. Bjørn and Hauschild [16] develop boundaries based on carrying capacity of regional ecosystems for the impact categories normally covered in LCA and propose their integration into the LCA methodology to support assessments of absolute environmental sustainability.

At the UN General Assembly 25 September 2015 in New York, UN member states adopted a set of 17 goals to 'end poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development agenda' [17]. The goals are accompanied by more detailed targets to be reached by 2030. Many of the goals have a relevance for manufacturing, but one of them – goal number 12 - specifically addresses Responsible Consumption and Production – Ensure sustainable consumption and production patterns, with some of the targets concerning

- sustainable management and efficient use of natural resources
- halving of food waste
- waste reduction through prevention, reduction, recycling and reuse
- environmentally sound management of chemicals
- dissemination of information about company practices that supports sustainable procurement and consumption

Also in 2015, the European Union launched its action plan for Circular Economy as a means to decouple resource use and consumption through much more circular product and material flows targeting repair and maintenance, remanufacturing, reuse and recycling [18]. Industry is given a central role with efforts on;

- eco-design,
- increased efficiency of manufacturing,
- reduced use of chemicals that may accumulate in materials through multiple material loops,
- business models based on concepts like product-service systems, sharing economy,
- increased use of recycled materials and resources,
- industrial symbiosis.

Engineering of products and technology in a life cycle perspective is essential to allow industry to deliver to these agendas.

3. Life Cycle Engineering (LCE) – from earlier attempts at a definition to frameworks

To achieve factor 10 improvements in the eco-efficiency of our overall technology by 2050 is a daunting task. As suggested by the UN sustainable development targets and the EU action plan on circular economy, it requires targeted engineering of all parts of the product and technology life cycles, from the primary sectors providing the raw materials over the design and development of new generations of products and manufacturing systems through their use and maintenance to decommissioning and end of life. As a consequence, companies that design and manufacture products are facing a complex situation with a wide range of requirements and methods and tools to address them. Companies often react to an increase of the external complexity with the development of inner structures. Examples are the establishment of new business units for environment or corporate social responsibility, hiring new staff in form of experts or introducing new methods and tools e.g. to enable life cycle assessment or total cost of ownership studies. Consequently, not only the external complexity but also the inner complexity is high. One the one hand consistent definitions can help to understand the meaning of life cycle engineering and related method and tools. On the other hand, frameworks can help to structure the life cycle perspective and therefore help to create orientation and get the necessary transparency to select and combine the right methods and tools [19].

In the early 1980s, the U.S. Defence Advanced Research Program Agency (DARPA) initiated investigations in so-called Unified Life-Cycle Engineering (ULCE) [20]. A more formal understanding of the life cycle engineering concept was presented during the early nineties [21-22]. Both of these references clearly state that LCE is a systematic “cradle to grave” approach and that it “provides the most complete environmental profile of goods and services” [21-22]. A later attempt at a definition of LCE is given by Jeswiet [23] as: “Engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste.” In their CIRP keynote, Hauschild et al. [24] expand this definition with a number of keywords, but the focus remains strong on design for environment and efficient manufacturing. Besides these attempts to define LCE a number of enabling methods, tools and techniques have been developed to support decision-making. All of these have been developed bottom-up and can be grouped under two categories, (1) those developed for a particular life cycle stage or activity with an influence on the entire life cycle, and (2) those developed as generic tools that can be used at any stage of the product life cycle. Examples of tools belonging to the first group are Green Material Selection, Design for Environment (DfE), Design for Disassembly (DfD), and Design for Recycling (DfR). These are all used during the design phase with a strong influence on other life cycle stages since up to 80% of the environmental footprint of a product is decided during the design phase. The second group counts more generic tools like LCA and LCC that can be applied to any and all stages of the product life cycle. As mentioned earlier, all of these tools have been developed in a bottom-up perspective with the aim to improve the performance in a relative perspective [11].

In addition to the methods and tools a number of different frameworks – especially at the management or company level were developed over the last decades. Some frameworks cluster life cycle relevant methods and tools with regard to the three dimensions of sustainable development and/or to the time horizon of the decision to be made, ranging from strategic to more operational perspective [25]. The importance of consistent data and information is stressed as a central element of the framework for Life Cycle Management (LCM) proposed by Westkämper and colleagues [26]. Based on the principles of the Viable System Model, Herrmann and colleagues developed a framework for Total Life Cycle Management centred around the life cycle and sustainable development as a normative principle. The framework further structures LCM into a strategic and an operational layer and distinguishes between life cycle spanning (e.g. environmental life cycle evaluation) and life cycle stage-related disciplines (e.g. after-sales management) that have to interplay synergistically [27-28]. Based on the environmental and temporal scope proposed by Coulter and colleagues [29] Herrmann positions (Total) Life Cycle Management on a single to multi-company level between Industrial Ecology and approaches typically related to LCE such as DfE and Life Cycle Design [28]. These framework attempts and the listed methods and tools all address an environmental concern but their focus is on relative improvements towards a more sustainable development without addressing the need for an absolute perspective.

Peças et al. [30] give a recent overview presenting the state of the art. In their paper, they present an LCE taxonomy accompanied by a literature review towards classifying existing tools and techniques with an attempt to structure them under the umbrella of their LCE taxonomy. The proposed taxonomy is based on the strategic management and system theories, which is useful in terms of structuring the existing tools. However, it does not help guiding LCE practitioners towards the target of creating engineering solutions that are sustainable in absolute terms, in order to stay within the planetary boundaries.

Considering the challenges to achieve sustainable manufacturing and the central role of life cycle engineering in addressing these challenges, there is a need for a systematic framework of life cycle engineering that organizes engineering activities throughout the life cycle of a product or a technology and positions them according to their leverage in terms promoting sustainable production systems. It is the ambition of this paper to meet this need.

4. An integrated framework

The proposed framework builds on previous attempts made by [28-29] and on the strong sustainability perspective and the role of manufacturing as presented in Figure 1. The space of the framework is defined by the temporal scope and the scope of environmental concern along the x-axis and the y-axis respectively (Figure 2).

Following a top-down approach Sustainability describes the wider space defined by the Earth's life support system and the span of our civilization. One level down at the edge of societies/economies and with a time scope between the generation lifetime and the civilization span, sustainable development is positioned expressing the continuous process of change. One level further down industrial ecology looks at industry and its surrounding systems [19]. Life cycle management covers all activities but also structures and behaviour of an organisation including normative management (e.g. organizational culture), strategic management (e.g. innovation behaviour) and operative management (e.g. operational learning) [28]. The framework sees the environmental dimension as the basis and boundary for economic and social sustainability. It defines the scope of LCE as looking at products from a multitude of different products to a single product over all stages of the life cycle(s), and structures LCE with regard to the main activities and life cycle stages (product development, raw material extraction, manufacturing, after-sales service/engineering, reuse, remanufacturing, recycling and disposal). Therefore, with activities comprising a multitude of different products and related to an integrated product and process life cycle planning with a temporal scope of one or more product life cycles, the interface between LCM and LCE is a floating transition zone [31]. In the framework, the scope of environmental concern deals with the type and scale of environmental impact both in terms of spatial or geographical scale and in terms of organisational level in Figure 1, ranging from the manufacturing system over society's entire economy and the overall impacts on society to the Earth's Life Support System, as considered in the setting of Planetary Boundaries. In this context, Planetary Boundaries are determined from a scientific understanding of the planet's biophysical subsystems or

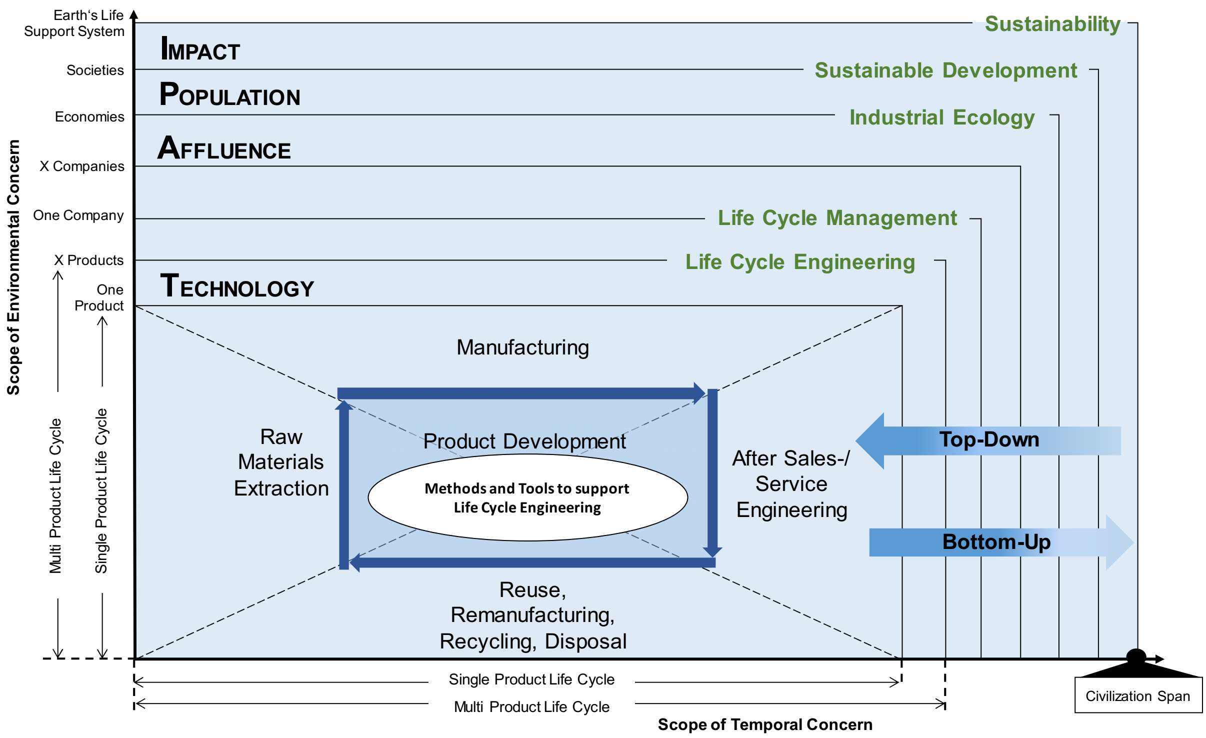

Fig. 2. Life Cycle Engineering framework placing manufacturing within the context of planetary boundaries and absolute sustainability (adopted from [27, 28]).

processes as the level of man-made environmental impact that does not compromise our ability to stay within a safe operating space for humanity with respect to the Earth system [32]. The scope of temporal concern deals with the time scale ranging from single and multi-product life cycles to the lifetime of a generation until the civilization span [28]. Along the two axes, the increase in temporal and environmental scope is linked to each of the four factors in the IPAT equation (Eq. 1). The technology factor T has the scope of one or multiple products in their life cycles and is determined by decisions made by product development. The affluence factor A has the scope of the economy and is influenced by the governance of and political management of the latter. The population factor P has societies' scope of environmental concern and the temporal scope of generations, while the Impact factor I representing our interference with the environment has the scope of Earth's life support systems and the temporal scope of civilisations.

When interpreting the proposed framework bottom-up, LCE is in the centre. Product development plays a central role for LCE as a large share of the later environmental impact is already decided at this stage. LCE methods and tools should help to support decision making towards the upper scopes of concern, orienting it towards absolute sustainability. With this, LCE is now defined as sustainability-oriented product development activities within the scope of one to several product life cycles. The methods and tools used in LCE must support reducing the total environmental impact associated with technology change and volume increase from one product generation to another, in order to ensure that new product technologies stay within their environmental space as derived from the planetary boundaries. Life cycle management (LCM) has to support this new understanding on a company level for instance with redefining the vision and mission of the company [28]. Industrial ecology, defined as an integrated systems approach to manage the environmental effects of using energy, materials, and capital in industrial ecosystems [33], has industrial symbiosis as a central element with exchange of waste streams between independent companies, and can hence be positioned at the economies level. The strategy of circular economy also addresses this scope. At the societal level, the role of life cycle engineering is to support a sustainable development of society, and considering the scope of Earth's life support system, the goal of life cycle engineering activities should be to ensure sustainability in the long term. This means meeting the needs of the present in a way that does not compromise the ability to meet the needs of future generations.

Using the framework, top-down and bottom-up approaches can thus be identified, establishing and clarifying relationships between LCE and the other fields with an aim to link them to the planetary boundaries and the concept of absolute sustainability. The motivation for the latter is the realisation that in order to support the development of sustainable production (and associated consumption) patterns, engineering activities and in particular, LCE must consider the planetary boundaries from the scope of both environmental and temporal concern. Central in this endeavour must be the attempt to bridge the gap between bottom-up engineering and requirements derived from top-down approaches such as the boundaries recently agreed for climate change impacts. In the core of the framework, the LCE activities are positioned as a cradle-to-grave product development activity. In order to foster sustainable development as a pathway towards a sustainable society, hence sustainability, all human activities, including LCE activities within an industry for current and future generations need to stay within this boundary. As presented previously, the IPAT equation (Eq. 1), can be used to determine the expected and wanted developments at higher scopes in the system and in a top-down approach determine the requirements that such developments pose to the more narrow scopes and in particular to LCE activities at the company or product level.

5. Refocusing Life Cycle Engineering (LCE)

All methods and tools as well as frameworks that have been developed over the years in different disciplines and within specific domains are targeting different problems or ambitions in relation to sustainability. As a result, there is often little synergy between them, and they completely lack the overall goal which must be achieving the sustainability of the system or technology in absolute terms. Therefore, they do not provide a pathway for the LCE practitioners to develop products and processes while taking the absolute boundaries for environmental sustainability into account. In addition, the main aim of LCE during product development has been expanded from the original focus on environmental impacts to include the economic dimension with the advent of the triple-bottom line concept, which again has led to trading off the economic dimension at the expense of the environmental and social dimensions. In order to refocus LCE efforts, it is imperative that the starting point of life cycle thinking and the foundation of LCE are well understood. The early roots of LCE in the mentioned Unified Life-Cycle Engineering (ULCE) [20] and the publications of Keoleian and Menerey [21] and Alting and Jørgensen [22] all present a more formal understanding of the LCE concept as a systematic "cradle to grave" approach that "provides the most complete environmental profile of goods and services". They go on to state that consideration of the entire life cycle helps designers "ensure that the environmental impact of their products are discovered and reduced, not merely shifted to other places." Although, the scope of this definition is one product life cycle, it is clear that the focus is on the environmental dimension, which is in line with the sustainability model given in Figure 1.

Therefore, it is imperative to revisit the grassroots and focus LCE with respect to its starting point: the concern about environmental impacts caused by technical products and processes. However, instead of focusing on efficiency and bottom-up thinking, the big-picture of (absolute) sustainability, top-down thinking, needs to be integrated for the LCE practices as shown in Figure 3. This figure makes an explicit attempt to bridge the gap between LCE activities such as life cycle planning and engineering of product technologies and the impact associated with the use of these technologies in the context of an increase in consumption and population.

New product technologies need to be life cycle engineered, not only for the single product and product life cycle (technology effect), but also for the anticipated volume growth as a result of consumption and population increase (volume effect) so that the associated total environmental impact can be taken into account during the product development stage. In order to stay within the absolute boundaries for environmental sustainability (e.g. the planetary boundaries) and achieve absolute sustainability, the total environmental impact of the new product generation must not exceed the space that is available for the activity. This normally means that it has to be less than the total environmental impact of the previous generation. If this is not attainable with the current product technologies, then the eco-efficiency limits are exhausted and a new eco-effective technology solution are to be sought, meaning that we have to strive for function and system innovation [34] or even beyond [25,35-36].

In the LCE domain, most methodologies, tools and techniques have been developed to guide product and process improvement or product and process reengineering aiming for relative improvement in environmental performance. In order to help LCE practitioners, new tools and techniques are required in the area of fundamental function and system innovation to support the leaps needed towards achieving absolute sustainability as indicated by the factor 10 improvements in the average technology factor required to meet the requirements for climate change by 2050. There is, however, a dearth of research into development of tools to guide LCE practitioners towards absolute sustainability and what does exist is limited. Examples are offered by the methodology used by Panasonic Company and Toshiba Company known as Factor X [37] and Factor T [38] that takes a ratio of the eco-efficiency of new product with respect to the benchmark product. Although these approaches are first step to improve product performance with respect to the previous generation, the main aim is still to improve the eco-efficiency of product technologies; hence it is a trade-off between environmental and economic objectives. The methodology proposed by Kim and co-workers, [39-40] is perhaps the first step towards developing tools for LCE practitioners to take into account technology and volume effect on the environment and benchmark the new generation environmental performance to the old generation. The main shortcoming of this approach is that it also does not provide an absolute upper-boundary within which the impact of the product generation must stay.

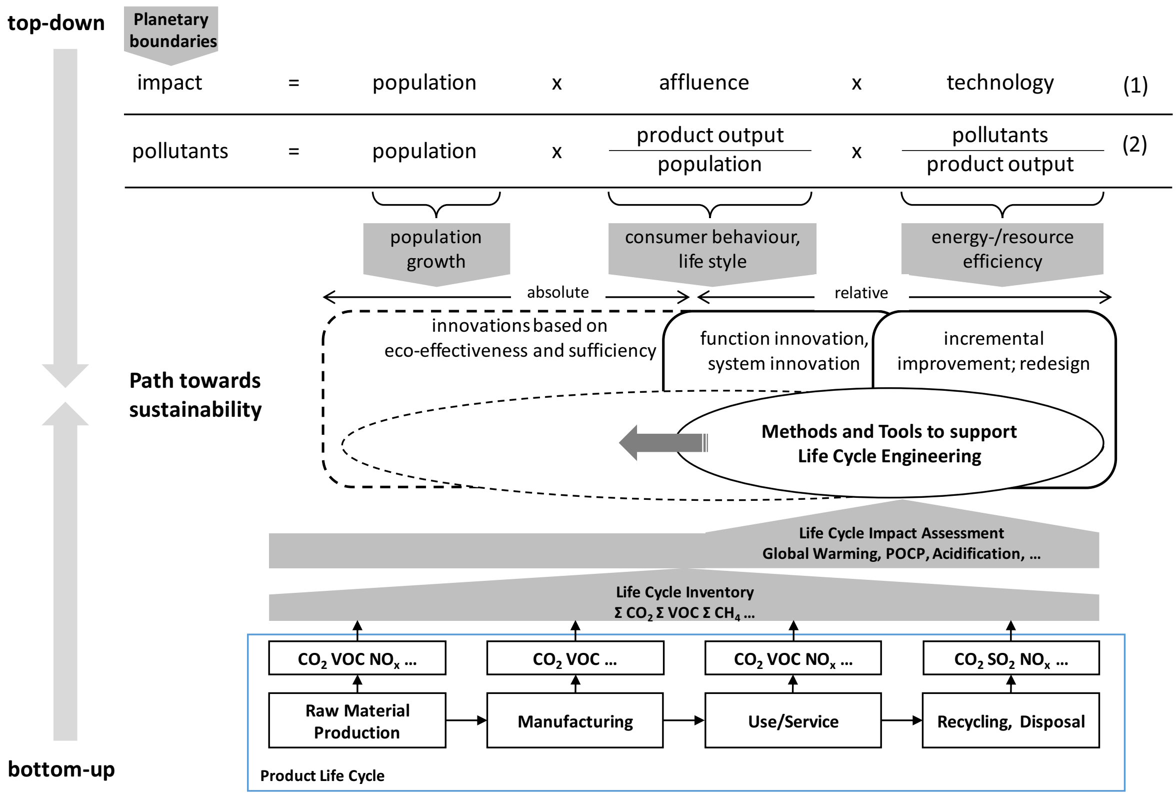

Fig. 3. Combining top-down and bottom up perspectives

Absolute boundaries at the level of companies or even individual products may be based on the boundaries presented by e.g. the Planetary Boundary framework or other science-based boundaries for man-made environmental impact (e.g. [14, 16]). These boundaries set an absolute limit for man-made environmental impacts that defines a total pollution quota or space that must not be exceeded. The space can be seen as a limited resource similar to other limited resources for which societal actors compete. The share of the space that can be occupied by an individual industry or manufacturer within the given industry should be determined to quantify the environmental space that the company is entitled to occupy. This will give manufacturers the freedom to exercise creativity within the environmental space allocated to them from a global sustainability limit but also the responsibility to keep their activities within this absolute boundary. The allocation of the space between different actors is tricky. Different criteria may be applied as basis of an allocation, and there is currently no agreement on a uniform criterion. The available space might be allocated among countries according to population figures. The resulting "personal environmental space" has been proposed for the normalisation step of life cycle impact assessment by [16]. Value creation might also be used as an allocation key when dividing the available environmental space between actors, and through the applied market mechanism, this is partly implemented in the existing system for distribution and management of global greenhouse gas emissions via trading of CO2-quota between countries and companies. If an environmental space should be divided as a pollution permit between individual corporations or branches, the allocation based on value creation might be preferable to many industries, since it ensures them a space that is proportional to their turnover. It would also favour those companies that are most efficient in creating value with a low environmental impact – the most eco-efficient companies, and it would provide a drive towards higher eco-efficiency of the manufacturer [41].

6. Conclusion remarks and future direction

With the presented life cycle engineering framework, we position manufacturing in the context of absolute environmental sustainability. By this, we hope to inspire an understanding of the roles and reaches of different LCE tools and activities. The framework emphasizes the need for an orientation of engineering activities towards achieving sustainable manufacturing that allows fulfilling needs of both present and future generations without exceeding the boundaries of Earth's life support systems. The traditional bottom-up approaches starting in the production process and the product, aiming for improved eco-efficiency must meet top-down approaches that define absolute targets for our production starting in the requirements that must be met to ensure environmental sustainability.

As mentioned above, the environmental concern was the original focus of LCE of the community in sustainability and the "shift" towards triple bottom line thinking, the picture became blurry and the unfocused as everybody was able to bring his own tools and approaches to the playing field of LCE. Instead of trying to classify and structure this multitude, the realization of the proximity of absolute boundaries for environmental sustainability calls on us to refocus and return to the starting point: environmental concern first. LCA or LCA driven approaches move into the centre instead of having LCA as just one approach out of many. From this perspective, we have derived a framework centred on LCA-based approaches from the bottom-up perspective and on IPAT-thinking framed by absolute environmental sustainability limits like the planetary boundaries from the top-down perspective. This new framework emphasizes the dearth of methods and tools that support LCE towards absolute and not only relative sustainability.

It is the hope of the authors that the introduction of an absolute sustainability perspective in the framework may inspire development of methods and tools needed to elevate LCE from being an exercise in eco-efficiency improvement to make it eco-effective with the development of technologies that support a sustainable production and consumption.

References

[1] UN. World population prospects: the 2015 revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, New York. 2015.

[2] World Commission on Environment and Development. Our common future. Oxford: Oxford University Press; 1987.

[3] Elkington J. Cannibals with forks. The triple bottom line of 21st century. New Jersey: Wiley. 1997.

[4] Gutés MC. The concept of weak sustainability. Ecological economics. 1996;17(3):147-56.

[5] Goodland R. The concept of environmental sustainability. Annual review of ecology and systematics. 1995:1-24.

[6] Rockström J. Bounding the planetary future: why we need a great transition. Great Transition Initiative. 2015.

[7] Ehrlich PR, Holdren JP. Impact of population growth. Science. 1971; 171(3977):1212-1217.

[8] Commoner B. The environmental cost of economic growth. In Ridker RG (ed.) Population, Resources and the Environment. Washington, DC: U.S. Government Printing Office 1972: 339-63.

[9] Field CB, Barros VR, Mastrandrea MD, Mach KJ, Abdrabo MK, Adger N, Anokhin YA, Anisimov OA, Arent DJ, Barnett J, Burkett VR. Summary for policymakers. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2014:1-32.

[10] Huppes G, Ishikawa M. Eco-efficiency and Its Terminology. Journal of Industrial Ecology. 2005;9(4):43-6.

[11] Hauschild MZ. Better–but is it good enough? On the need to consider both eco-efficiency and eco-effectiveness to gauge industrial sustainability. Procedia CIRP. 2015;29:1-7.

[12] Hertwich EG. Consumption and the rebound effect: An industrial ecology perspective. Journal of industrial ecology. 2005;9(1‐2):85-98.

[13] Kim SJ, Kara S, Kayis B. Analysis of the impact of technology changes on the economic and environmental influence of product life-cycle design. International Journal of Computer Integrated Manufacturing. 2014;27(5):422-433.

[14] Bjørn A, Diamond M, Owsianiak M, Verzat B, Hauschild MZ. Strengthening the link between life cycle assessment and indicators for absolute sustainability to support development within planetary

boundaries. Environmental science & technology. 2015;49(11):6370-6371.

[15] Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C. Planetary boundaries: Guiding human development on a changing planet. Science. 2015;347(6223): 736-746.

[16] Bjørn A, Hauschild MZ. Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level. The International Journal of Life Cycle Assessment. 2015;20(7):1005-1018.

[17] UN. Sustainable development goals. United Nations Sustainable Development. 2016.

[18] EU Commission. Closing the loop - An EU action plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels: COM. 2015.

[19] Herrmann C, Hauschild M, Gutowski T, Lifset R. Life cycle engineering and sustainable manufacturing. Journal of Industrial Ecology. 2014 ;18(4):471-477.

[20] Calkins DE, Gaevert RS, Michel FJ, Richter KJ. Aerospace System Unified Life Cycle Engineering Producibility Measurement Issues. Alexandria VA: Institute for Defense Analyses; 1989.

[21] Keoleian GA, Menerey D. Life cycle design guidance manual. Washington, DC: U.S. EPA Office of Research and Development. 1993.

[22] Alting DL, Jøgensen DJ. The life cycle concept as a basis for sustainable industrial production. CIRP Annals-Manufacturing Technology. 1993;42(1):163-167.

[23] Jeswiet J. A definition for life cycle engineering. 36th International seminar on Manufacturing Systems. 2003.

[24] Hauschild M, Jeswiet J, Alting L. From life cycle assessment to sustainable production: status and perspectives. CIRP Annals-Manufacturing Technology. 2005;54(2):1-21.

[25] Saur K, Donato G, Flores EC, Frankl P, Jensen AA, Kituyi E, Lee KM, Swarr T, Tawfic M, Tukker A. Draft final report of the LCM definition study. UNEP/SETAC Life cycle initiative. 2003.

[26] Westkämper E. Life cycle management and assessment: approaches and visions towards sustainable manufacturing. CIRP Annals-Manufacturing Technology. 2000 Dec 31;49(2):501-526.

[27] Herrmann C, Bergmann L, Thiede S, Halubek P. Total Life Cycle Management-An Integrated Approach Towards Sustainability. 3rd International Conference on Life Cycle Management. 2007.

[28] Herrmann C. Ganzheitliches Life Cycle Management. Berlin: Springer; 2010.

[29] Coulter S, Bras B, Foley C. A lexicon of green engineering terms. 10th International conference on engineering design. 1995.

[30] Peças P, Götze U, Henriques E, Ribeiro I, Schmidt A, Symmank C. Life Cycle Engineering–Taxonomy and State-of-the-Art. Procedia CIRP. 2016;48:73-8.

[31] Umeda Y, Takata S, Kimura F, Tomiyama T, Sutherland JW, Kara S, Herrmann C, Duflou JR. Toward integrated product and process life cycle planning-An environmental perspective. CIRP Annals-Manufacturing Technology. 2012 Dec 31;61(2):681-702.

[32] Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B. A safe operating space for humanity. Nature. 2009;461(7263):472-5.

[33] Frosch RA, Gallopoulos NE. Strategies for manufacturing. Scientific American. 1989;261(3):144-52.

[34] Brezet H. Dynamics in ecodesign practice. Industry and environment. 1997;20(1-2):21-4.

[35] Dyllick T, Hockerts K. Beyond the business case for corporate sustainability. Business strategy and the environment. 2002;11(2):130-41.

[36] Young W, Tilley F. Can businesses move beyond efficiency? The shift toward effectiveness and equity in the corporate sustainability debate. Business Strategy and the Environment. 2006;15(6):402-15.

[37] Aoe T. Eco-efficiency and ecodesign in electrical and electronic products. Journal of Cleaner Production. 2007;15(15):1406-14.

[38] Toshiba. Advancing Together with Factor T. 2009.

[39] Kim SJ, Kara S, Kayis B. Economic and environmental assessment of product life cycle design: volume and technology perspective. Journal of Cleaner Production. 2014;75:75-85.

[40] Kim SJ, Kara S. Predicting the total environmental impact of product technologies. CIRP Annals-Manufacturing Technology. 2014;63(1):25-8.

[41] ECCJ. Top Runner Program: Developing the world’s best energy-efficient appliances. Eenergy Convervation Center, Japan. 2015.